The Scintillation Velocity of the Relativistic Binary Pulsar PSR J1141–6545

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ABSTRACT

We report a dramatic orbital modulation in the scintillation timescale of the relativistic binary pulsar J1141–6545 that both confirms the validity of the scintillation speed methodology and enables us to derive important physical parameters. We have determined the space velocity, the orbital inclination and even the longitude of periastron of the binary system, which we find to be in good agreement with that obtained from pulse timing measurements. Our data permit two equally-significant physical interpretations of the system. The system is either an edge-on binary with a high space velocity (~ 115 km s^{-1}) or is more face-on with a much slower velocity (~ 45 km s^{-1}). We favor the former, as it is more consistent with pulse timing and the distribution of known neutron star masses. Under this assumption, the runaway velocity of 115 km s^{-1} is much greater than is expected if pulsars do not receive a natal kick at birth. The derived inclination of the binary system is $76 \pm 2.5°$ degrees, implying a companion mass of 1.01 ± 0.02 M$_\odot$ and a pulsar mass of 1.29 ± 0.02 M$_\odot$. Our derived physical parameters indicate that this pulsar should prove to be an excellent laboratory for tests of gravitational wave emission.

Subject headings: pulsars:general – pulsars:individual PSR J1141–6545 – pulsars:binary – ISM: scintillation

1. Introduction

The scintillation observed in the radio wavelength emission from pulsars is considered to be a result of diffraction of the incident wave front around small scale irregularities in the interstellar medium (ISM) (Rickett 1969). The characteristic timescale for these scintillation events can be hours, minutes, or even seconds and is highly dependent upon a number of factors: the distance to the source; the relative velocities of the source, observer and

scattering material; the observing frequency; and the structure and distribution of the ISM (Cordes, Pidwerbetsky, & Lovelace 1986; Cordes & Rickett 1998). It has long been considered possible that observations of binary pulsars would reveal a modulation in scintillation velocity due to their orbital motion relative to the scattering medium (Lyne & Smith 1982). Such orbital modulation in the scintillation velocity of a binary pulsar has been significantly detected only in the circular binary PSR B0655+64 (Lyne 1984). Dewey et al. (1988) have reported a weak orbital modulation of scintillation velocity in observations of PSR B1855+09 and PSR B1913+16, but were unable to constrain any system parameters.

The ideal pulsar for such measurements would scintillate on timescales much smaller than the orbital period and have enough flux to obtain high signal-to-noise ratios within the scintillation timescale. In addition, the orbital period should be much less than the timescale for changes in the scintillation parameters due to macroscopic variations in the structure of the ISM. Finally, the pulsar should display large variations in its transverse orbital velocity.

The relativistic binary pulsar, PSR J1141–6545, was recently discovered in the Parkes multibeam pulsar survey (Kaspi et al. 2000). It has a spin period (P) of 394 ms, a very narrow ($0.01P$) pulse, a dispersion measure of 116 pc cm^{-3} and is in an eccentric, 4.7 hr orbit. It is thought to be a member of a new class of object that has a young neutron star in an eccentric orbit with a massive $\sim$1 M$_\odot$ white dwarf companion. Kaspi et al. (2000) found no evidence for scintillation. We have searched specifically for short–timescale scintillation and found that the pulsar scintillates on timescales of minutes with a characteristic bandwidth of just $\sim$1 MHz at a central observing frequency of 1390 MHz. At the Parkes 64 m observatory it completes two orbits during its transit time, changes velocity by over 200 km s^{-1}, and has a short orbital period. In every respect, this pulsar is an ideal target for scintillation work. Recent neutral Hydrogen observations (Ord, Bailes & van Straten 2002) place the binary at least as distant as the Carina–Sagittarius spiral arm, which is 3.7 kpc away in the direction of PSR J1141–6545.

Unlike their progenitors, the massive O and B stars, radio pulsars have very large space velocities of up to 1000 km s^{-1} (Lyne, Anderson, & Salter 1982; Bailes et al. 1989; Harrison, Lyne, & Anderson 1992). The origin of pulsar velocities is difficult to ascertain as individual pulsars give little clues regarding the responsible physical mechanism (Radhakrishnan & Shukre 1986; Dewey & Cordes 1987; Bailes 1989). Eccentric binary pulsars, on the other hand, are fossil records of the state of a binary before detonation of the pulsar progenitor. In the absence of a natal kick, a binary pulsar has a well-defined relationship between its eccentricity, the amount of mass ejected during the formation of the neutron star, and the runaway velocity (Radhakrishnan & Shukre 1986). However, eccentric binary pulsars are rare and it has not been possible to make a definitive statement about kicks from an analysis

of their space velocities and orbital configurations (Cordes & Wasserman 1984; Hughes & Bailes 1999; Wex, Kalogera, & Kramer 2000). Kaspi et al. (1996) have shown that the massive binary PSR J0045–7319 has a precessing orbit consistent with the pulsar receiving an impulsive kick at birth. In the case of PSR J1141–6545, the space velocity, had the pulsar received no natal kick, should be small as the eccentricity is low. But evolutionary arguments concerning the minimum diameter of the progenitor (Tauris & Sennels 2000) suggest that its runaway velocity should be at least 150 km s^{-1}.

In this paper, we present the detection of an orbital modulation of the scintillation velocity in observations of PSR J1141–6545. The effect is very significant, permitting the determination of a number of system parameters. Measurements have been obtained of the most probable space velocity and inclination of this system, as well as the longitude of periastron. As with the analysis of PSR B0655+64 by Lyne (1984), there is a clear degeneracy between two distinct solutions of equal significance. In this case, however, the degeneracy can be broken: one of the solutions indicates an unreasonably low neutron star mass. The structure of this paper is as follows: in section 2 we describe our observations and methodology for determining the scintillation parameters; section 3 describes the model and our fitted results; finally, in section 4 we discuss the results and their implications for future relativistic observables and the origin of pulsar velocities.

2. The Observations and Data Reduction

PSR J1141–6545 was observed on the 27th of January 2002 for approximately ten hours, using the Parkes 64 m radio telescope. The 512×0.5 MHz filterbank centred at 1390 MHz was used with the centre element of the Parkes multi-beam receiver (Staveley-Smith et al. 1996). In each filterbank channel, the power in both linear polarisations was detected and summed before 1 bit sampling the total intensity every 250 μs. The results were written to magnetic tape for offline processing.

Average pulse profiles were produced by folding the raw data in each 500 kHz frequency channel modulo the topocentric pulse period. An integration time of 29 seconds provided sufficient resolution to resolve the scintillation structure throughout the orbit. For each profile, the mean level of the off-pulse region was subtracted from that of the on-pulse region to produce a dynamic spectrum. Figure 1 shows the clear orbital modulation of the dynamic spectrum. In each orbital period, there is an obvious apparent vertical "blurring" as the scintillation timescale varies.

In order to model the physical parameters of the binary system, we require estimates of

the pulsar's velocity as a function of orbital phase. Individual measurements of the transverse velocity were obtained at different epochs throughout the observation by determining the scintillation timescale and bandwidth. These were derived from the two-dimensional autocorrelation function (ACF).

Individual ACFs were calculated over a small region of the dataset that spanned approximately 12 minutes in the time domain and 24 MHz in the frequency domain. A two-dimensional fast Fourier transform (FFT) was calculated and multiplied by its complex conjugate to form the ACF. To improve the signal-to-noise ratio, a single ACF was formed at each timestep by combining all the ACFs produced across the bandpass. The scintillation timescale was defined to be the $1/e$ full width of a Gaussian fit to the central peak of the ACF in the direction of increasing time-lag. Following convention (Cordes 1986), the scintillation bandwidth was defined to be half the width at half-height of a Gaussian fit across the frequency lags.

By moving the ACF window through the dynamic spectrum with a timestep of one time lag, or 29 seconds, scintillation parameters were assigned a time corresponding to the central lag of the ACF. These values were integrated into 32 binary phase bins using the ephemeris presented by Kaspi et al. (2000). The value of the scintillation velocity was determined using the following relationship.

$$V_{\mathrm{ISS}} = 2.53 \times 10^4 \frac{(D\Delta\nu_{\mathrm{d}})^{1/2}}{f\tau_{\mathrm{d}}} \tag{1}$$

Equation 1 is after Cordes and Rickett (1998). V_{ISS} is the scintillation velocity, D is the earth-pulsar distance in kpc, $\Delta\nu_{\mathrm{d}}$ is the scintillation bandwidth in MHz and τ_{d} is the scintillation timescale in seconds. The constant multiplicative factor is the value determined by Cordes and Rickett (1998) for a uniform Kolmogorov scattering medium. The distance used was 3.7 kpc (Ord, Bailes & van Straten 2002). Any uncertainty is incorporated into a scaling parameter within the model.

This process produced the scintillation velocity as a function of mean orbital anomaly. The system is significantly eccentric ($e \sim 0.17$) and the model described in §3 constructs the velocity as a function of true, not mean, orbital anomaly. We therefore transform the observed scintillation velocity into a function of eccentric anomaly, η, by an iterative solution of Kepler's equation, $\epsilon = \eta + e\sin\eta$, where ϵ is the mean anomaly. Eccentric anomaly is converted into true anomaly, θ, via a simple trigonometric relationship:

$$\tan\frac{\theta}{2} = \sqrt{\frac{1+e}{1-e}}\tan\frac{\eta}{2}. \tag{2}$$

3. The Model

To determine the most probable runaway velocity and inclination angle of this system, we constructed a model that calculated the transverse velocity as a function of five free parameters. These were: the components of the transverse velocity along and perpendicular to the *line of nodes*, $v_{\rm plane}$, and $v_{\rm per}$, respectively; the orbital inclination angle, i; a scaling factor, κ; and the longitude of periastron, ω. The latter is accurately determined by pulse timing, and allows us to confirm the validity of our results.

The orbital velocity was calculated as a function of true orbital anomaly (θ) and broken into a radial component directed toward the focus of the orbital ellipse in the line of nodes ($v_{\rm r}$), the second component was perpendicular to $v_{\rm r}$ and in the direction of the orbital motion, v_θ.

In this framework, the space velocity as a function of true orbital anomaly is given by:

$$v_{\rm r} = \frac{2\pi x c}{\sin i(1-e^2)^{1/2}P_{\rm b}} e\sin\theta \qquad (3)$$

$$v_\theta = \frac{2\pi x c}{\sin i(1-e^2)^{1/2}P_{\rm b}}(1+e\cos\theta) \qquad (4)$$

where the observable $x = (a/c)\sin i$ is the projected semi-major axis in seconds, a is the semi-major axis of orbit, i is the inclination of the system, e is the orbital eccentricity and $P_{\rm b}$ the binary period.

After the construction of the binary model, the next stage was to transform this orbital velocity into a predicted scintillation velocity.

Assuming that the Earth had a near constant velocity throughout the observation and that the interstellar medium velocity was small compared to that of the pulsar, the model of the transverse velocity ($V_{\rm model}$) was described by the following equations:

$$v' = \left((v_r\cos\phi - v_\theta\sin\phi) + v_{\rm plane}\right), \qquad (5)$$

$$v'' = \left((v_\theta\cos\phi + v_r\sin\phi)\cos i + v_{\rm per}\right), \qquad (6)$$

$$V_{\rm model} = \kappa\sqrt{v'^2 + v''^2}. \qquad (7)$$

The angle $\phi = \omega + \theta$ is the true anomaly measured with respect to the line of nodes. The model parameter κ was included to incorporate any errors introduced in the conversion of scintillation timescale to velocity into the model. This accounts for errors in the distance to the pulsar and the fact that the scattering medium is not uniform. The model was then evaluated at the same 32 values of true anomaly presented by the dataset. The best fit to the model was found by evaluating the chi-squared statistic throughout a wide range of each

of the model parameters. This produced a chi-squared volume of 5 dimensions with a global minimum representing the most probable values of the 5 parameters.

A box-car smoothing operation was also applied to the model in order to compensate for the averaging introduced by the auto-correlation process. This had little effect on the values of the fitted parameters but did appreciably lower the chi-squared minimum.

The relative errors in each binary phase bin were calculated by first determining the scatter in each phase bin. The best fit to the data was found by location of the global minimum in the chi-squared space, and the error bars were normalised to ensure the reduced chi-squared statistic was unity. This enabled errors to be placed upon the estimates of the fitted parameters by examining the chi-squared distribution. It should be noted that this method assumes *a priori* that the model was a valid description of the data. A Monte Carlo analysis was then performed in order to ascertain the precision of the fitted parameters. This analysis demonstrated that the model described the observations particularly well and the range of allowable parameter values was very narrow.

Both the measured values of $V_{\rm ISS}$ and the best-fit model velocity, $V_{\rm model}$, are plotted as a function of true anomaly in Fig 2.

3.1. The effects of Refractive Interstellar Scintillation

The analysis described above would not have revealed any underlying systematic error introduced by either random or long-term variations in the scintillation timescale that are not associated with changes in the velocity of the pulsar. For example, the interstellar scintillation effects detailed here are a result of diffractive interstellar scintillation (DISS), but another regime of scintillation is refractive interstellar scintillation (RISS). RISS, which has a characteristic timescale generally much longer than that of DISS, was considered by Romani, Narayan and Blandford (1986) to be the explanation for the long term flux variability in pulsars observed by Sieber (1982). Although the effect of RISS is best characterised via multiple flux measurements, it is possible to estimate the RISS timescale, $T_{\rm RISS}$, using the measured DISS parameters:

$$T_{\rm RISS} = 150.6 \left(\frac{D({\rm kpc})}{\Delta\nu({\rm kHz})V_7^2}\right)^{1/2} {\rm days}. \tag{8}$$

Equation 8 is after Blandford and Narayan (1985). It assumes a uniform Kolmogorov medium and that the pulsar is travelling at $100V_7\,{\rm km\ s^{-1}}$. In Equation 8 D represents distance and $\Delta\nu$ is the scintillation bandwidth. If the velocity of the source can be approximated by the measured scintillation velocity, then $T_{\rm RISS}$ is approximately 7 days. It is

therefore unlikely that a modulation of this nature was present in the observation. Even if it was present, the modulation would be weak as RISS effects are considerably weaker than DISS events (Rickett 1990). For these reasons, the effect of RISS was discounted in this analysis. Future observations, if they span multiple days, may be prone to RISS effects that limit the precision of derived parameters.

4. Results

As discussed by Lyne (1984), analyses of this nature can produce two indistinguishable solutions. The degeneracy arises as the same apparent transverse velocity can be displayed by the pulsar in either a comparatively face-on binary system with a low runaway velocity, or a more edge-on system with a higher runaway velocity. An example of this can be seen in the chi-squared projection presented in Figure 3. The values of the fit parameters for both solutions after the Monte Carlo error analysis are presented in Table 1. The degeneracy between solutions can be broken by a reasonable consideration of the mass function and other timing parameters. Kaspi et al. (2000) derive a value for the mass function, $f(M) = 0.176$ $M_\odot$, and an estimation of the sum of the system component masses, $M_c = 2.3$ $M_\odot$, from timing measurements. Using these measurements, together with the system inclination presented here, the component masses may be obtained. The more edge-on solution indicates a pulsar and companion mass of 1.29 ± 0.02 $M_\odot$ and 1.01 ± 0.02 $M_\odot$ respectively; whereas the more face-on solution, suggests a pulsar mass of 1.17 ± 0.02 $M_\odot$ and a companion mass of 1.13 ± 0.02 $M_\odot$. The edge-on solution is more likely as the indicated pulsar mass is more consistent with the known neutron star mass distribution, 1.35 ± 0.04 $M_\odot$ (Thorsett & Chakrabarty 1999). The most probable transverse velocity is therefore found to be of modulus 115 ± 15 km s^{-1}, and the most likely inclination angle is $76 \pm 2.5°$.

In order to test the validity of the experimental method employed and the accuracy of the binary model, we allowed the angle of periastron to vary as a free parameter in the fit. The value of ω is already precisely determined by timing measurements and its value at the epoch of these observations is expected to be approximately 55.13°. The consistency of this with our measurement of 58 $\pm 3.5°$ is very encouraging and increases our confidence in the solution which is extremely statistically significant.

5. Discussion

PSR J1141–6545 has been shown to have a transverse velocity of modulus $115 \pm 15\,\mathrm{km\,s^{-1}}$ and an inclination of $76 \pm 2.5°$. The component masses inferred from these values indicate, as first presented by Kaspi et al. (2000), that this system is most likely a near edge-on neutron star–CO white dwarf binary, with the observed neutron star having been formed most recently.

Tauris and Sennels (2000) have predicted, from evolutionary arguments, that PSR J1141–6545 would display a systemic velocity in excess of 150 $\mathrm{km\,s^{-1}}$. This velocity comes from both the recoil of the binary due to the rapid ejection of the exploding star's envelope, and an impulsive kick imparted to the neutron star to leave it in an orbital configuration resembling the current state of PSR J1141–6545. The "no-kick" solution, suggests a velocity nearer 40 km $\mathrm{s^{-1}}$. The measured transverse velocity is only consistent with that predicted by Tauris & Sennels (2000), if the undetected radial velocity exceeds 96 $\mathrm{km\,s^{-1}}$. The simulations undertaken by Tauris & Sennels (2000) suggested that 150 km $\mathrm{s^{-1}}$ was the lower limit, and that PSR J1141–6545 would probably have a velocity much greater than this. The low tranverse velocity indicates that, as with the other eccentric binary pulsars, the kick was modest (Hughes & Bailes 1999).

It is also interesting to note that Ord, Bailes & van Straten (2002) give a lower distance limit to this system as the tangent point distance, 3.7 kpc. At this distance, and with a transverse velocity of 115 ± 15 km $\mathrm{s^{-1}}$, the expected contribution to any measured orbital period derivative due to proper motion and Galactic kinematic effects is expected to be at the 1 percent level. Furthermore, measurements of the range and shape of Shapiro delay, advance of periastron, gravitational redshift parameter and gravitational period derivative will over-determine the system parameters. Together with the determination of the system inclination presented here, estimates of these parameters will allow precise and unique tests of the validity of General Relativity.

This result suggests that long-term monitoring of its scintillation properties throughout a year may ultimately provide the orientation of the proper motion vector on the sky. An independent measure of the orbital period, eccentricity, longitude of periastron and inclination angle of the binary should also be obtained.

REFERENCES

Bailes, M. 1989, Astrophys. J., 342, 917

Bailes, M., Manchester, R. N., Kesteven, M. J., Norris, R. P., & Reynolds, J. E. 1989, Astrophys. J., 343, L53

Blandford, R. D. & Narayan, R. 1985, Mon. Not. R. astr. Soc., 213, 591

Cordes, J. M., Pidwerbetsky, A., & Lovelace, R. V. E. 1986, Astrophys. J., 310, 737

Cordes, J. M. & Rickett, B. J. 1998, ApJ, 507, 846

Cordes, J. M. & Wasserman, I. 1984, Astrophys. J., 279, 798

Dewey, R. J. & Cordes, J. M. 1987, Astrophys. J., 321, 780

Dewey, R. J., Cordes, J. M., Wolszczan, A., & Weisberg, J. M. 1988, in Radio Wave Scattering in the Interstellar Medium ,AIP Conference Proceedings No. 174, ed. J. Cordes, B. J. Rickett, & D. C. Backer (New York: American Institute of Physics), 217–221

Harrison, P. A., Lyne, A. G., & Anderson, B. 1992, in X-ray Binaries and Recycled Pulsars, ed. E. P. J. van den Heuvel & S. A. Rappaport (Dordrecht: Kluwer), 155–160

Hughes, A. & Bailes, M. 1999, Astrophys. J., 522, 504

Kaspi, V. M., Bailes, M., Manchester, R. N., Stappers, B. W., & Bell, J. F. 1996, Nature, 381, 584

Kaspi, V. M., Lyne, A. G., Manchester, R. N., Crawford, F., Camilo, F., Bell, J. F., D'Amico, N., Stairs, I. H., et al., 2000, Astrophys. J., 543, 321

Lyne, A. G. 1984, Nature, 310, 300

Lyne, A. G., Anderson, B., & Salter, M. J. 1982, Mon. Not. R. astr. Soc., 201, 503

Lyne, A. G. & Smith, F. G. 1982, Nature, 298, 825

Ord, S. M., Bailes, M., & van Straten, W. 2002, Mon. Not. R. astr. Soc., submitted

Radhakrishnan, V. & Shukre, C. S. 1986, Astrophys. Space Sci., 118, 329

Rickett, B. J. 1969, Nature, 221, 158

Rickett, B. J. 1990, Ann. Rev. Astr. Ap., 28, 561

Romani, R. W., Narayan, R., & Blandford, R. 1986, Mon. Not. R. astr. Soc., 220, 19

Sieber, W. 1982, Astr. Astrophys., 113, 311

Staveley-Smith, L., Wilson, W. E., Bird, T. S., Disney, M. J., Ekers, R. D., Freeman, K. C., Haynes, R. F., Sinclair, M. W., et al., 1996, Proc. Astr. Soc. Aust., 13, 243

Tauris, T. M. & Sennels, T. 2000, Astr. Astrophys., 355, 236

Thorsett, S. E. & Chakrabarty, D. 1999, Astrophys. J., 512, 288

Wex, N., Kalogera, V., & Kramer, M. 2000, Astrophys. J., 528, 401

System Parameter	Solution 1	Solution 2
κ	1.55 ± 0.025	1.55 ± 0.025
$v_{\rm plane}$	15 ± 10 km s^{-1}	20 ± 10 km s^{-1}
$v_{\rm per}$	115 ± 10 km s^{-1}	40 ± 10 km s^{-1}
i	$76 \pm 2.5°$	$60 \pm 2.5°$
ω	$58 \pm 3.5°$	$58 \pm 3.5°$
Pulsar mass	1.29 ± 0.02 M$_\odot$	1.17 ± 0.02 M$_\odot$

Table 1: The two degenerate best fits to the data. Solution 1 is more likely, as the pulsar mass is more consistent with the current distribution of known neutron star masses.

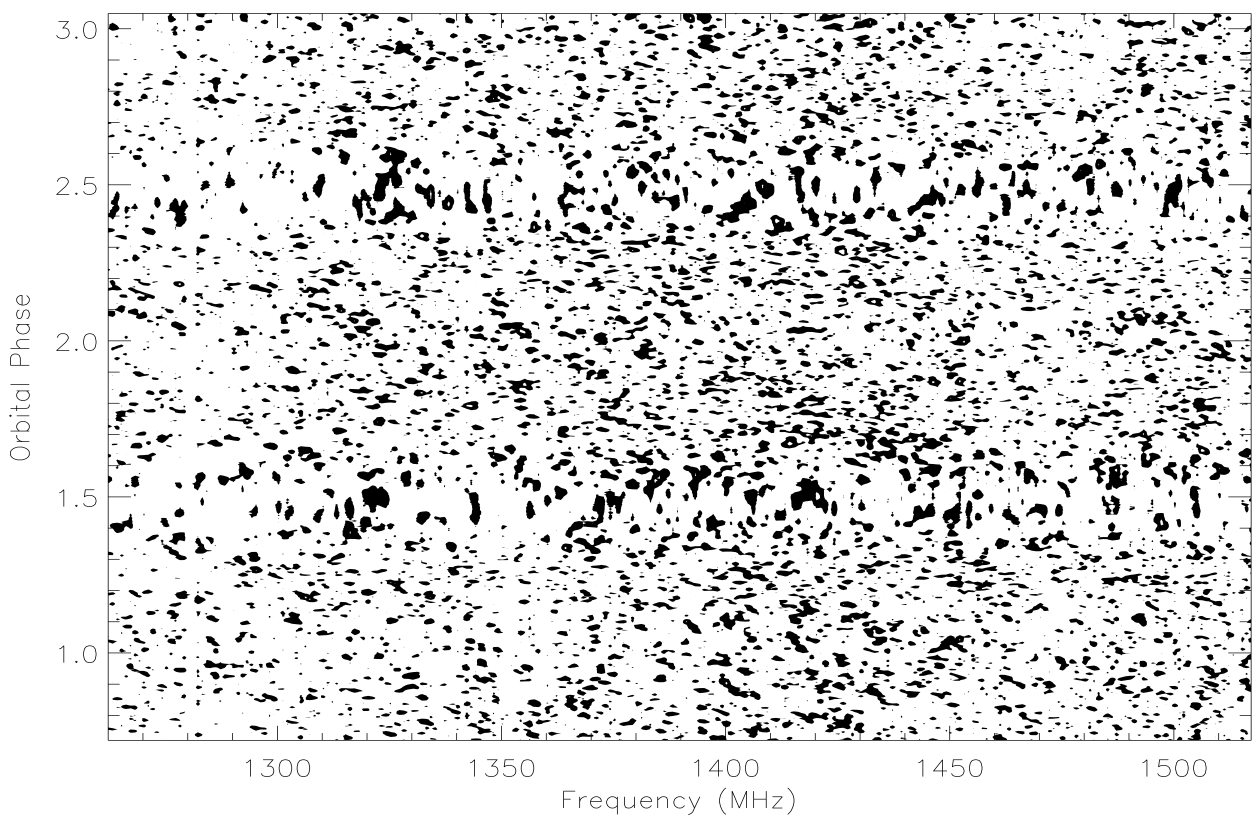

Fig. 1.— The dynamic spectrum for PSR J1141–6545 represents the pulsar flux as a function of time and radio frequency. The plot is presented as a two level grey scale for emphasis. The vertical blurring once per orbit is interpreted as a lower relative speed in the plane of the sky.

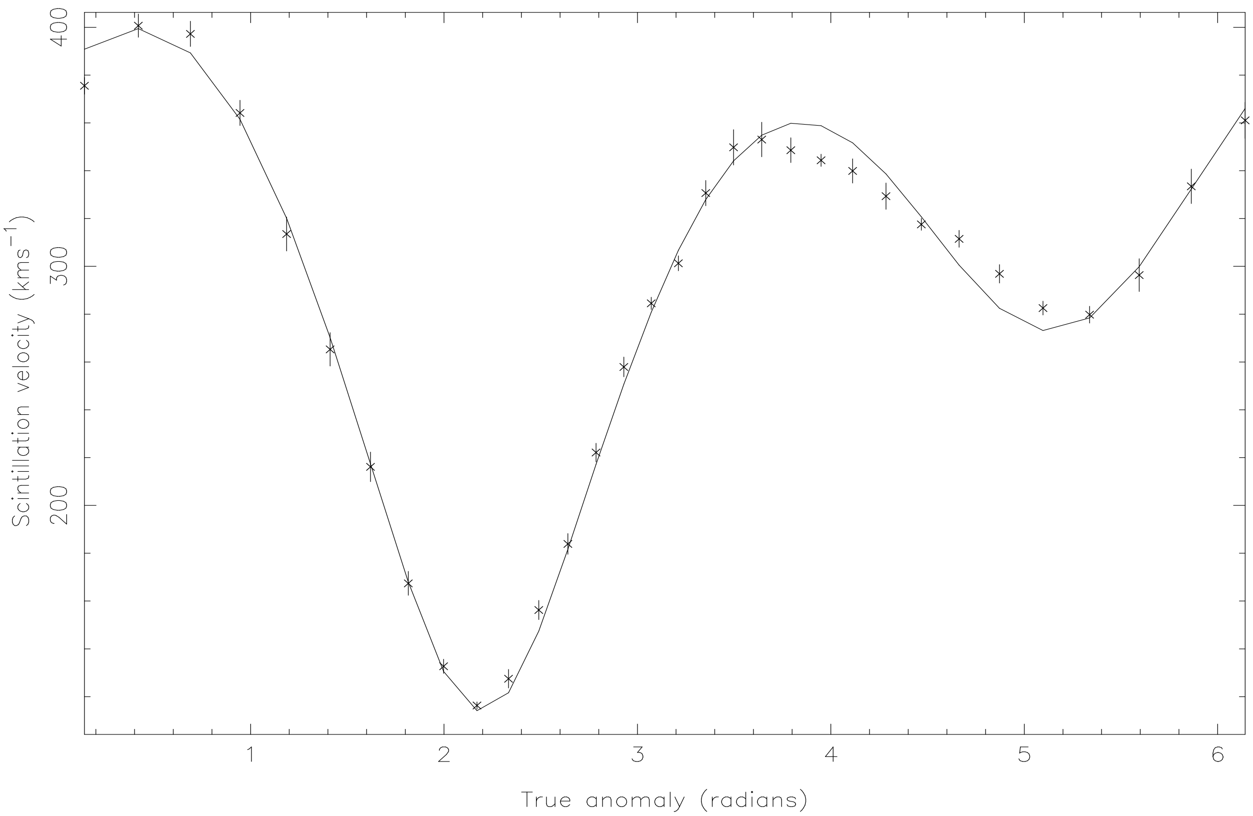

Fig. 2.— – A plot of scintillation velocity versus true anomaly for the relativistic binary pulsar, PSR J1141–6545. The solid line represents the best-fit model. Velocity estimates are plotted with their one sigma errors, as determined using a χ^2 normalization technique.

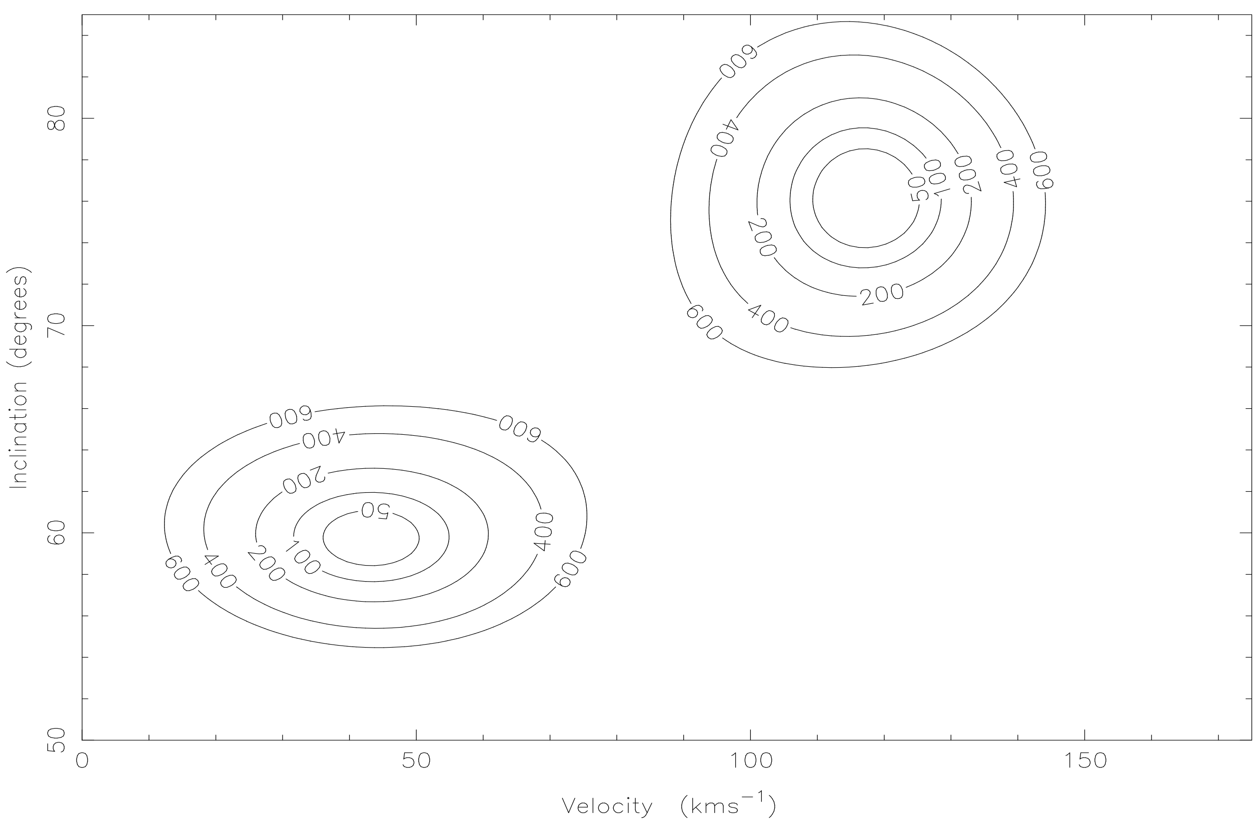

Fig. 3.— The projection of the delta-chi-squared volume into the dimensions of orbital inclination and transverse velocity. The two distinct solutions are evident.